

THE DESIGN AND ENHANCEMENT OF A TESTBED FOR THE  
REMOTE SYSTEM MONITORING INTERFACE DEVICE TECHNOLOGY

A Senior Honors Thesis

by

REGAN CHRISTOPHER TURNER

Submitted to the Office of Honors Programs  
& Academic Scholarships  
Texas A&M University  
in partial fulfillment of the requirements of the

UNIVERSITY UNDERGRADUATE  
RESEARCH FELLOWS

April 2003

Group: Engineering & Physics I

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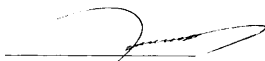
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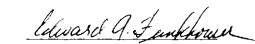
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Approved as to style and content by:



Alexander G. Parlos  
(Fellows Advisor)



Edward A. Funkhouser  
(Executive Director)

April 2003

Group: Engineering & Physics I

## ABSTRACT

The Design and Enhancement of a Testbed for the  
Remote System Monitoring Interface Device Technology. (April 2003)

Regan C. Turner  
Department of Mechanical Engineering  
Texas A&M University

Fellows Advisor: Dr. Alexander G. Parlos  
Department of Mechanical Engineering

Texas A&M University has developed an information technology-based system that is able to continuously monitor and diagnose faults of electrical motors, based solely on electrical signals available at the motor terminals, such as current and voltage readings. The system relies on developments in advanced signal processing. Such a monitoring system is very cost-effective and a new engineering field has developed, named "sensorless motor diagnostics." The monitoring system will rely on previously developed algorithms to analyze components of a decomposed electrical signal. The individual component signal information can then be used to determine system health and detect early signs of mechanical failure [1].

In this project, an existing testbed was modified and to enable Texas A&M researchers to gather and analyze data from a network of electric motors. The testbed system includes a 3-hp motor connected to a dynamic load and a 1-hp motor connected to an inertial load. Accelerometers can be used to gather vibration data from the components and specially-designed sensors collect data from the electrical signals. The

modified testbed now provides Texas A&M with a viable research medium that will allow attempts to prove the feasibility of implementing continuous data collection of equipment vitality information from industrial and/or governmental equipment by direct or indirect linkage to a common electric power system.

## **ACKNOWLEDGMENTS**

I would like to thank Dr. Alexander G. Parlos of the Texas A&M Mechanical Engineering Department for his assistance, guidance, and knowledge throughout the past two years. Additionally, all testing and experimentation would not have been possible without the assistance of Mr. Parasuram Harihara.

## TABLE OF CONTENTS

	Page
ABSTRACT .....	iii
ACKNOWLEDGMENTS .....	v
TABLE OF CONTENTS.....	vi
LIST OF FIGURES .....	vii
LIST OF TABLES .....	viii
INTRODUCTION .....	1
DESCRIPTION OF TESTBED .....	4
Description of Spectraquest Testbed .....	4
Description of Texas A&M Testbed .....	4
MODIFICATIONS PERFORMED ON TEXAS A&M TESTBED .....	8
Installation of Pump System .....	8
1-HP Motor & Load Design .....	9
TESTBED EXPERIMENTAL RESULTS .....	14
Steady State Results .....	14
Transient Results .....	16
CONCLUSION .....	19
REFERENCES .....	20
VITA .....	21

## LIST OF FIGURES

Figure	Page
1 Example of Remote Monitoring Using Sytem Interface Device Technology.....	2
2 Gearbox End of Testbed Prior to Enhancement .....	5
3 Electrical Input End of Testbed Prior to Enhancement .....	6
4 Simple Schematic of Enhanced Texas A&M Testbed .....	6
5 Connection Between Pump and Gearbox .....	9
6 Torque-Speed Curve and Best-Fit Line for 1-HP Motor .....	10
7 Steady State Current Readings Using 60Hz Input .....	15
8 Steady State Current Readings Using Variable Transformer .....	15
9 Transient Current Readings of 3hp Motor for Case 1 at 60 Hz.....	16
10 Transient Current Readings of 1hp Motor for Case 2 at 60 Hz .....	17
11 Transient Current Readings of 3hp Motor for Case 2 at 60 Hz .....	18
12 Transient Current Readings of 1hp Motor for Case 2 Using Variable Transformer .....	18

## LIST OF TABLES

Table	Page
1 Torque-Speed Properties of 1-HP Motor .....	10
2 Target Properties of Inertial Load .....	13
3 Dimensions of Disk Designed to Meet Target Inertial Load Properties .....	13



## 1. INTRODUCTION

Components of rotating electrical machinery are subject to a variety of different types of failures. For example, mechanical vibrations, heat, age, and oil contamination may lead to insulation break-down in stator windings [2]. Rotor bars may fail due to a combination of stresses acting upon the rotor [2]. Improper lubrication, unbalanced loads, and misalignment can cause excessive wear in machine bearings [2]. Such failures lead to down-time in industrial applications, which is accompanied by a significant loss of profits and available resources. Fault detection and diagnosis aim to provide warning of impending failures of electrical motors, leading to extended plant life, higher quality of products, and greater plant availability [1].

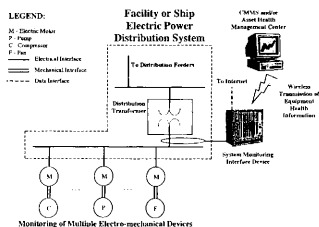
At the present, most industrial equipment owners maintain critical machinery by (1) random checks using on-site diagnostic data gathering and analytical maintenance strategies, or (2) operation until failure. Practice such as this results in large expenditures in emergency maintenance and significant loss of revenue due to equipment and facilities downtime. Operations and maintenance budgets could be significantly reduced with the automation of current maintenance and prevention strategies; in practice, the continuous retrieval of equipment health information. Two technological "roadblocks" stand in the way of such an operation. First, current methods of such data collection are not cost-effective. Second, delivery of the vital information to proper decision-making authority is difficult. Currently, many industrial equipment

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are not linked to any data acquisition system for continuous monitoring of system vitality. To retrofit such systems with required sensors would come at a large capital expense. Once this information is gathered, it must be delivered to a central location for interpretation, due to a scarcity of maintenance troubleshooting experts.

Texas A&M University is developing an information technology-based system that is able to continuously monitor and diagnose faults of electrical motors, based solely on electrical signals such as current and voltage readings available at the distribution transformer. The monitoring system will rely on previously developed algorithms to analyze components of a decomposed electrical signal. The individual component signal information can then be used to determine system health and detect early signs of mechanical failure. Wireless communication technologies can transmit signals from a remote location, allowing for greater implementation of this technology. A schematic of an example motor network is displayed in Figure 1



**Figure 1: Example of Remote Monitoring Using System Interface Device Technology**

In this project, a testbed was designed that will enable Texas A&M researchers to gather and analyze data from such a network of electric motors. The testbed system includes a 3-hp motor connected to a dynamic load and a 1-hp motor connected to an inertial load. Specially-designed sensors collect current and voltage readings from the electrical signals sent to the motors. With the construction of this testbed, we aim to prove the feasibility of implementing continuous data collection of equipment vitality information from industrial and/or governmental equipment by direct or indirect linkage to a common electric power system.

## **2. DESCRIPTION OF TESTBED**

This section describes the Texas A&M University testbed, both as it was before this project, and after.

### **2.1 DESCRIPTION OF SPECTRAQUEST TESTBED**

In 2001, Texas A&M University purchased a testbed from Spectraquest, a leading developer of machinery diagnostics systems. The original testbed consisted of a 250 V, 3-phase, 3-hp motor connected to a rotor deck. Dial gauges allow the user to simulate eccentricities in the rotor deck. Accelerometers measure vibration on the rotor deck, and a torque meter between the motor and the rotor deck measures the torque of the motor. None of the original components of the testbed was removed in the modification process.

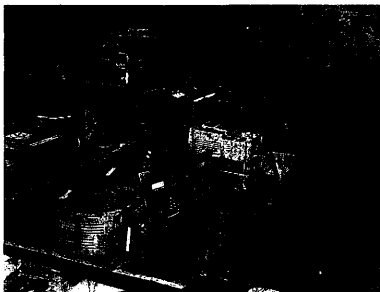
### **2.2 DESCRIPTION OF TEXAS A&M TESTBED**

The proposed concept will begin development of an interface device that would acquire data and uplink it to a remote, asset health management system. Specifically, this project is the design of a testbed that will enable Texas A&M researchers to gather and analyze data from a network of electric motors. Experiments run on this testbed will be used to prove the feasibility of implementing continuous data collection of equipment vitality information from industrial and/or governmental equipment by direct or indirect linkage to a common electric power system.

This project analyzed and modified a basic testbed that was built by Spectraquest<sup>66</sup> in 2001 to create a simple model of industrial systems that feature multiple motors. The testbed is powered by a 250 V, 3-phase electrical source, much like the power sources used in industrial plants. Initially, the testbed consisted of only a single sensor used to collect the component currents and voltages transmitted to a 3-hp motor connected to a gearbox that drove a pump system—a dynamic load.<sup>1</sup> Photographs of the testbed prior to enhancement are seen in Figure 2 and Figure 3.

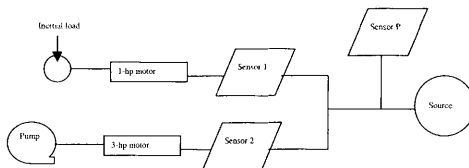


**Figure 2: Gearbox End of Testbed Prior to Enhancement**



**Figure 3: Electrical Input End of Testbed Prior to Enhancement**

To model actual industrial applications, however, it is desirable to have a testbed with multiple motors, thus requiring multiple sensors to obtain all electrical signal data. To provide such a model, this project enhanced the testbed to include a 1-hp motor connected to an inertial load and added additional sensors to the network. A simple schematic of this layout can be seen in Figure 4.



**Figure 4: Simple Schematic of Enhanced Texas A&M Testbed**

The 1-hp motor runs in parallel with the 3-hp motor. Individual sensors, shown in Figure 4 as *Sensor 1* and *Sensor 2*, monitor the motors by collecting current and voltage readings. Additionally, a third sensor collects composite electrical signals that are sent to the two-motor network and is represented by *Sensor P*.

## 4. MODIFICATIONS PERFORMED ON TEXAS A&M TESTBED

This section describes the modifications made to the testbed after it was purchased from Spectraquest.

### 4.1 *Installation of Pump System*

The first step in modifying the testbed was the installation and alignment of a pump system to the gearbox, providing dynamic loading for the 3-hp motor. Figure 5 shows the pump and gearbox connection after pump installation. To mount the pump system, the following steps were employed:

1. Visual inspection was used to determine where holes should be drilled in the testbed.
2. The holes were then drilled and threaded using a threading tool.
3. The pump was affixed to the testbed using hex-head screws.
4. Dial gauges were employed to check the alignment between the gearbox shaft and the pump shaft. Thin aluminum shims were placed under the pump base to correct any vertical misalignments.

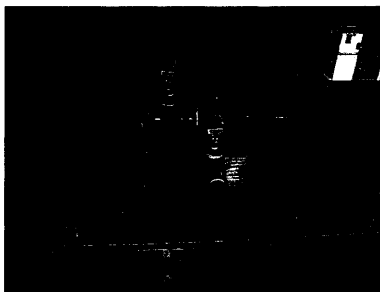


Figure 5: Connection Between Pump and Gearbox



To mount the valve through which water in the system will be pumped, steps 1-3 of the above procedure were repeated. No alignment was necessary because there is no mechanical power transmission to the valve from the rotating machinery.

## **4.2 1-HP Motor & Load Design**

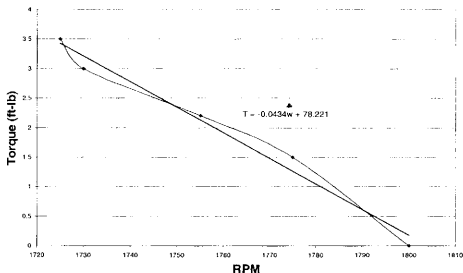
Following installation of the pump and valve, a 1-hp motor was added in parallel with the 3-hp motor. The 3-hp motor is a totally enclosed, three phase c-face Marathon Electric motor with a rigid base.<sup>2</sup> To maintain uniformity within the testbed, a 1-hp motor of the same specifications was purchased for the system.<sup>3</sup>

To minimize vibrations of the 1-hp motor, it was mounted on a 3/4"-thick steel plate measuring approximately 12" x 16". Rubber feet on the bottom of the steel plate prevent the motor from "walking" while it runs.

When conducting experiments on a scaled testbed such as this, it is desirable to operate motors with a full load to simulate industrial applications. A *full load* for the motor is defined as a load of the maximum possible that will not cause the motor to stall. Determining the full-load characteristic of the 1-hp motor required knowledge of the motor's torque-speed properties and basic rotary-disk theory. The torque-speed properties of the motor, available from Marathon Electric, are given in Table 1.

**Table 1: Torque-Speed Properties of 1-HP Motor**

Load	RPM	Torque (ft-lb)
No Load	1800	0.0
1/2 Load	1775	1.5
3/4 Load	1755	2.2
1.0 Load	1730	3.0
1.15 Load	1725	3.5

**Figure 6: Torque-Speed Curve and Best-Fit Line for 1-HP Motor**

Using this torque-speed data, it is possible to determine a relationship between the torque and speed for any load, using a best-fit curve of the data. This relationship, along with the best-fit curve of the data, is shown in Figure 6.

The equation of the best-fit line is given by:

$$T = -0.0434\omega + 78.221 \text{ \{ft-lb\}} \quad (1)$$

Basic rotary disk theory gives [3]

$$J \frac{d\omega}{dt} + b\omega = T_{elec} \quad (2)$$

Where  $J$  is the inertia of the disk,  $b$  is the damping coefficient of the motor's shaft,  $T_{elec}$  is the electrical torque of the motor, and  $\omega$  is the angular velocity of the disk. To further

simplify the analysis, basic assumptions about the 1-hp motor and disk system were made. Because the shaft of the motor is less than 2" in length, the damping coefficient of the shaft was assumed to be zero. This yielded

$$\frac{d\omega}{dt} = \frac{T_{elec}}{J} \Rightarrow dt = \frac{J}{T_{elec}} d\omega \quad (3)$$

Integrating,

$$t = J \int_0^{\omega_{med}} \frac{1}{T_{elec}} d\omega \quad (4)$$

Where  $\omega_{med}$  is obtained from the motor's torque-speed curve and  $t$  is the rise time of the 1-hp motor and disk system. Solving for the inertia of the disk,

$$J = \frac{t}{\int_0^{\omega_{med}} \frac{1}{T_{elec}} d\omega} \quad (5)$$

Using Eq. (1) and assuming a rise time of  $t=1.0$  seconds for the system and an angular velocity of  $\omega = 1730 \text{ RPM} = 181.17 \text{ rad/s}$ , the target inertia of the disk is given numerically by

$$J = \frac{1.0}{\int_0^{181.17} \frac{1}{-0.0434\omega + 78.221} d\omega} \{ \text{lb-ft}^2 \} \quad (6)$$

Finally, this gives the maximum inertial load of the 1-hp motor to be

$$J = 0.410 \{ \text{lb-ft}^2 \} \quad (7)$$

To account for any underestimation of the actual full load of the motor, a safety factor of  $SF=2$  was introduced. The corrected maximum inertial load is then

$$J = 0.205 \{ \text{lb-ft}^2 \} \quad (8)$$

Based upon this desired property of the motor's inertial load, a disk was designed for the motor. Inertia of a disk is given by

$$J = \frac{1}{2} mr^2 \quad (9)$$

Where  $m$  is the mass of the disk and  $r$  is its radius.

With the 1-hp motor mounted on its steel base, the center of the motor's shaft is approximately 3.5" from the surface of the base. As mentioned previously, the shaft itself is less than 2" long. It is therefore reasonable to assume a disk radius of no more than 3" and a thickness of less than 1". The disk thickness must be constrained to allow for a restraint collar on the shaft to prevent the disk from coming off during experimentation. Steel was selected for the material of the disk due to its hardness and density, which was taken to be  $\rho=489 \text{ lb/ft}^3$ .

**Table 2: Target Properties of Inertial Load**

Density of Steel ( $\text{lb/ft}^3$ )	489
$J$ ( $\text{lb-ft}^2$ )	0.410
Safety Factor	2
$J_{\text{corr}}$ ( $\text{lb-ft}^2$ )	0.205

The disk's material density and its desirable inertia, radius, and thickness provided all necessary parameters for the design phase. The ideal properties of the inertial disk are given in Table 2. Using the Solver feature of Microsoft Excel®, dimensions of the disk were determined that fit within both inertial properties and size parameters of the motor are shown in Table 3.

**Table 3: Dimensions of Disk Designed to Meet Target Inertial Load Properties**

Thickness (in)	Radius (in)	Disk Vol (ft <sup>3</sup> )	Weight (lb)	Inertia (lb-ft <sup>2</sup> )
0.750	3.000	0.012	6.004	0.188

The designed disk has a thickness of 0.75 in. and a radius of 3.0 in., giving a volume of 0.012 ft<sup>3</sup>. It provides an inertial load to the motor of 0.188 lb-ft<sup>2</sup>, approximately 8% less than the target inertial load of 0.205 lb-ft<sup>2</sup>. The relative difference is within acceptable range, and design was carried forward to construction.

Machining of the disk took place in the machine shop of the Texas A&M University Mechanical Engineering Department, using AISI 1020 steel. Additionally, a small restraint collar was constructed of aluminum to prevent the disk from moving during experimentation.

Future additions to the testbed will include eccentric disks for the 1-hp motor. Their design will incorporate the same rotary-disk theory as the concentric disk machined for this project. When loading the 1-hp motor, an eccentric disk will produce an oscillating load, thereby requiring an oscillating electrical input to the motor.

## 5. TESTBED EXPERIMENTAL RESULTS

Experiments were conducted using two different input sources for the testbed, a variable transformer at 60 Hz and an inverter. Electrical signal data was collected from the 1-hp motor, the 3-hp motor, and at the main power bus. The 1-hp motor was loaded with the ideally designed disk and the 3-hp motor was loaded with the rotor deck of the testbed. Current and voltage signals were collected from the sensors using LabView at a sampling rate of 960 Hz.

### 5.1 *Steady State Results*

For data collection at steady state, the 3-hp motor was powered up initially. Once it reached steady state, the 1-hp motor was powered up. Current and voltage readings were then recorded continuously from both motors and at the main power supply. Current readings from 60 Hz inverter input are shown in Figure 7. As can be seen, the 3-hp motor uses a current of approximately  $\pm 3.5$  amps and the 1-hp motor uses a current of approximately  $\pm 3.0$  amps. The main power supply uses a current of approximately  $\pm 6.5$  amps, clearly a sum of the two motor currents.

Current readings from variable transformer input are shown in Figure 8. As with the results of the inverter input, the two individual motor signals sum to produce the composite signal. The current readings for the variable transformer input are slightly higher than those of the inverter input because the variable transformer uses more voltage than the inverter, 220V as opposed to 208V, respectively.

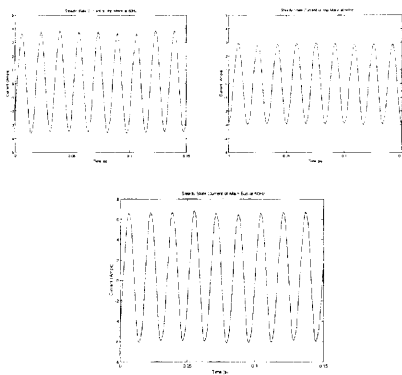


Figure 7: Steady State Current Readings Using 60Hz Input

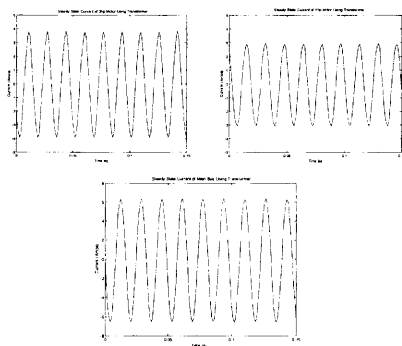


Figure 8: Steady State Current Readings Using Variable Transformer

## 5.2 Transient Results

For data collection of motors in transient state, continuous current and voltage readings were taken with both motors off. Then, two different cases were examined during for data collection:

1. The 3-hp motor was powered up. After it reached steady state, the 1-hp motor was powered up.
2. The 1-hp motor was powered up. After it reached steady state, the 3-hp motor was powered up.

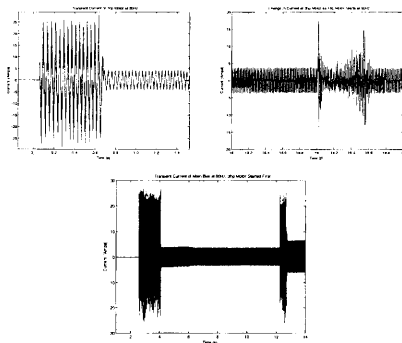
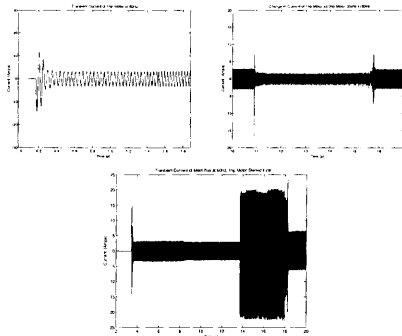


Figure 9: Transient Current Readings of 3hp Motor for Case 1 at 60 Hz

Figure 9 shows the current overshoot of the 3hp motor as it starts using the inverter input, its change as the 1 hp motor powers up once the 3hp motor reaches steady state, and the composite current reading. Likewise, Figure 10 displays the startup of the 1hp motor with inverter input and its current change once the 3hp motor powers up.



This data thus demonstrates that the testbed can record transient currents with inverter input.



**Figure 10: Transient Current Readings of 1hp Motor for Case 2 at 60 Hz**

Similar experiments were conducted using a variable transformer as electrical input to ensure that the testbed gives accurate results for both types of input. Figures 11 & 12 demonstrate that the testbed records changes in electrical signal over time using a variable transformer as input.

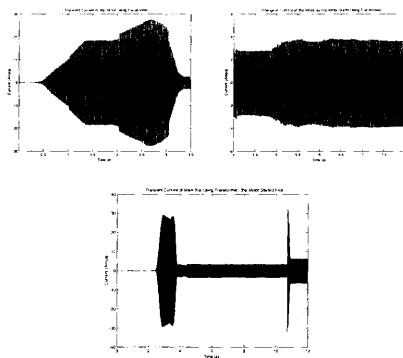


Figure 11: Transient Current Readings of 3hp Motor for Case 2 at 60 Hz

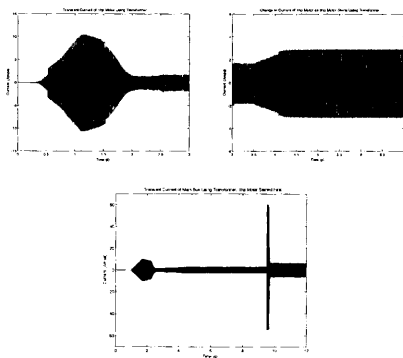


Figure 12: Transient Current Readings of 1hp Motor for Case 2 Using Variable Transformer

## 6. Conclusion

Electrical signal readings for individual motors in Texas A&M's modified testbed combine to produce the composite signal reading at the main power supply. This was demonstrated for two different types of electrical input, a variable-frequency inverter, and a variable-voltage transformer. Therefore, this project produced a testbed that accurately records electrical signals of the motors in its network and is a viable medium for collecting data that can be used in fault diagnosis of rotating machinery.

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<sup>1</sup> Note: The factory-designed gearbox ratio proved inadequate for powering the pump system, and was later replaced by a gearbox with a ratio of 1:1.67.

<sup>2</sup> Model #182T1FR4042, Catalog #U710

<sup>3</sup> Model #56T17F5315, Catalog #G563

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## Regan C. Turner

1882 Deer Trail  
Floresville, TX 78114

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### EDUCATION

Texas A&M University, College Station, TX  
Major in Mechanical Engineering  
Minors in History and Mathematics

U.S. Marine Corps Officer Candidates School,  
Quantico, VA  
Graduate of Platoon Leader's Course (PLC)  
July 2000 (Juniors), July 2002 (Seniors)

### ACADEMIC-ENRICHMENT EXPERIENCE

- Texas A&M Academy of Future International Leaders, Spring 2003
- Enrollment in AGED 641, a graduate course in Leadership Development, as an undergraduate student, Spring 2003
- Anticipated completion of Advanced International Affairs Certificate, A&M Bush School of Government, Summer 2003
- University Undergraduate Research Fellow, Texas A&M Honors Program, 2003
- Texas A&M Summer Study Abroad in Krakow, Poland, Summer 2001
- Engineering Scholars Program, 1998 - 2003

### HONORS AND AWARDS

- *Craig C. Brown Senior Engineer Award, Fall 2002*—Top award for graduating seniors in the Dwight Look College of Engineering
- *United States Marine Corps Commandant's Trophy, Summer 2000*—Top overall graduate of 241 USMC Officer Candidates from across the U.S., based upon leadership, academic success, and physical fitness
- *Buck Weirus Spirit Award, Spring 2002*
- *President's Endowed Scholar, Texas A&M Honors Program*
- *Galen C. Brown Foundation Scholar, Texas A&M Honors Program*
- *Kelly Castleberry Memorial Saber Award, Spring 2001*—Top-ranking USMC cadet at Texas A&M
- *Top Academic Sophomore, Texas A&M Corps of Cadets, Spring 1999*

### PUBLICATIONS/PRESENTATIONS

Turner, R.C., Design and Enhancement of a Testbed for the Remote System Monitoring Interface Device Technology, *Student Research Week Conference*, Texas A&M University, 2003.